Search For Hyper-deformation
Nuclei at Extreme Spins
or
Ultra Cold Fusion

Using Beams from the RIA Facility

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Several attempts have been made to experimentally verify the existence of a hyper-deformed (HD) minimum in the nuclear potential energy surface. Such a minimum, created by shell effects and stabilized by rapid rotation, has been predicted by a number of theorist [1] [2], and is calculated to become yrast at very high spins ($> 70\hbar$).

Searches for the discrete band transitions emitted while the nucleus is trapped **and cold** in this minimum has been unsuccessful [3] [4] [5]. It might be that the nucleus never gets cold enough over a sufficiently long time period for a cascade of closely spaced discrete γ rays to be emitted. The only evidence that we therefore may get for the existence of the HD minimum is from the γ rays emitted while the nucleus is relatively hot in this minimum. In that case, because the level density is high and there are many bands, a quasi-continuum (QC) of γ rays are emitted which will exhibit characteristic ridges in a γ-γ matrix or planes in a γ-γ-γ cube. The first hints of evidence for HD were indeed found in QC spectra (of $\approx^{153}$Dy, see [6] and [7]).

A prerequisite for observing HD is that the nucleus is formed at extremely high spins ($\approx$70 $\hbar$) where the HD states yrast or near yrast. At such high spins, fission is quite likely; but *can* be suppressed by carefully selecting cold reactions to populate the residues! It might well be that the searches so far for HD have failed because the fission cut off the higher partial waves that are needed to populate the nucleus in a HD state. To investigate this, a search for all all the possible reactions that can populate the particularly interesting nucleus ^{168}Yb by a 3n, 4n or 5n reaction at a spin 70 $\hbar$ was undertaken. In particular, the search was for ultra cold reactions - i.e. reactions where as little energy as possible is left in the residue – even when populated at $\approx$70 $\hbar$. How cold a residue can be formed depends both on the beam and target mass–excess values as well as how efficiently angular momentum can be transferred to the compound system. With only stable beam and stable target combinations it is obviously not always possible to create a nucleus as cold as desirable.

Of particular interest are fusion reactions that form the residue ^{168}Yb since this nucleus is calculated to be one of the best candidates in which to search for HD [1]. Figure 1 shows all the possible reactions that can populate ^{168}Yb by a 3n, 4n or 5n reaction at a spin of 70 $\hbar$ in the compound nucleus. The (backdrop) red circles have no restrictions on beam and target combinations – except requiring that the Q–value is known [9]. Thus, both beams and targets are unstable. The big black squares represents reactions where both the beam and the target are stable, i.e., reactions that can be made with the current stable beam accelerators on stable targets. The

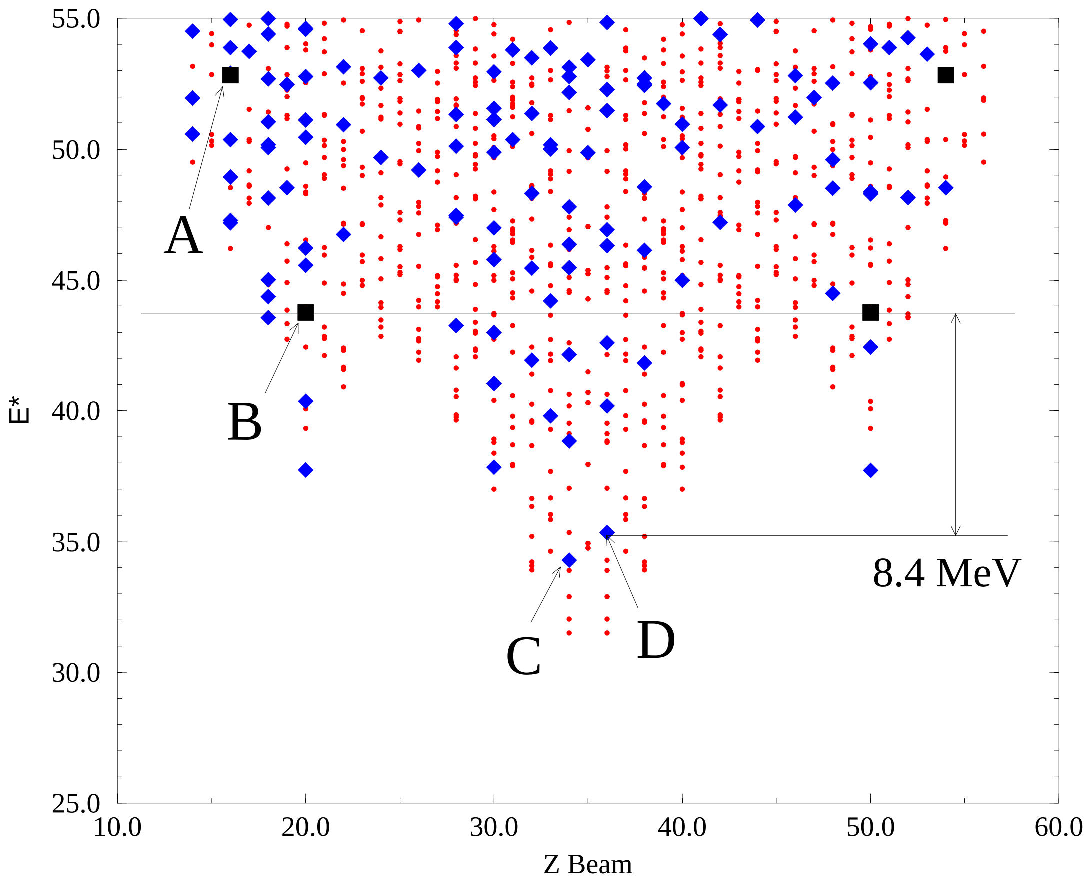

Figure 1: Graphical representation of all 3n, 4n and 5n reactions that can form the residue ^{168}Yb in a heavy ion fusion reaction where ≈70 $\hbar$ of angular momentum is broad into the compound nucleus. The x axis is the Z of the beam and the y axis is the excitation in ^{168}Yb after the q–value for the reaction had been added. Red circles have no restrictions on beam target combinations except that it is required that the mass excess is known [9]. The big black squares represents reactions where both the beam and the target are stable, i.e., reactions that can be made with the current stable beam accelerators. The blue diamonds are reactions where the target is is stable and the beam possibly produced and accelerated by a RIA facility. Selected reactions discussed in the text are labeled from A to D.

blue diamonds are possible *new* reactions that can be used with beams accelerated by the RIA facility on stable targets[1]. Some particularly interesting reactions are marked and listed in table 1. The mass excess for the isotopes discussed are given in table 2.

[1]Not all RIA beams and stable target combinations shown are necessarily feasible.

label	reaction	Q–value	E_{cms}	E^*
A	${}^{136}_{54}$Xe(${}^{36}_{16}$S,n)${}^{168}_{70}$Yb	140.63	-87.80	52.84
B	${}^{124}_{50}$Sn(${}^{48}_{20}$Ca,4n)${}^{168}_{70}$Yb	146.92	-103.16	43.77
C	${}^{86}_{36}$Kr(${}^{87}_{34}$Se,5n)${}^{168}_{70}$Yb	162.93	-128.63	34.30
D	${}^{82}_{34}$Se(${}^{91}_{36}$Kr,5n)${}^{168}_{70}$Yb	163.04	-127.69	35.35

Table 1: Selected reactions indicated in figure 1. The sum of the energy available in the CMS system,E_{cms}, and the Q–value is the total excitation energy E^* available when the neutrons are emitted.

The beam energy is always chosen so that $\approx$70 $\hbar$ is is available in the compound nucleus according to the formula:

$$Lmax = 0.8 \times 0.219 \times (R_{cb} + R_{touch})\sqrt{\mu \times (E_{CMS} - E_{CB})} \tag{1}$$

where

$$\begin{aligned} R_{cb} &= 1.2(A_1^{\frac{1}{3}} + A_2^{\frac{1}{3}}) \\ E_{cb} &= 1.44\frac{Z_1 Z_2}{R_{cb}+R_{touch}} \\ R_{touch} &\approx 2.0 \\ \mu &= \frac{A_1 A_2}{A_1+A_2} \\ E_{CMS} &= \frac{M_2}{M_1+M_2}E_1 \end{aligned} \tag{2}$$

This formula can be derived from the equation on top of page 587 of ref [8] using the impact parameter

$$b = 1.2(A_1^{\frac{1}{3}} + A_2^{\frac{1}{3}}) + R_{touch}, \tag{3}$$

i.e., the impact parameter of a system where the beam and the target nuclei just touch within a distance of $R_{touch} \approx 2.0$ fm. The factor of 0.8 is traditionally applied to take into account the smearing of the spin distribution and indicate the approximate maximum of the spin distribution as a function of the impact parameter.

It is clearly seen in figure 1 that only very few stable beam on stable target combinations can populate ${}^{168}_{70}$Yb without resulting in too much excitation energy in the residue. Of those, only reactions B is really useful since an Xe gas cell target is hard to use. The ${}^{124}_{50}$Sn(${}^{48}_{20}$Ca,4n)${}^{168}_{70}$Yb reaction has traditionally been used to populate ${}^{168}_{70}$Yb; but it is clearly seen from figure 1 that this reaction does not populate the nucleus as cold as possible. Thus, fission is not suppressed very well since the fission probability at high spins is a strong non–linear function of the excitation energy. However, with beams from a RIA facility on stable targets, is is possible to populate ${}^{168}_{70}$Yb more than 8 MeV colder using the ${}^{82}_{34}$Se(${}^{91}_{36}$Kr,5n)${}^{168}_{70}$Yb reaction. The ${}^{86}_{36}$Kr(${}^{87}_{34}$Se,5n)${}^{168}_{70}$Yb reaction would be even colder; but, again, a Kr gas cell target is difficult to make.

The unstable ${}^{91}_{36}$Kr beam (with a lifetime of 8.6 seconds) is an easy beam for the RIA facility to produce by the well understood two–step ISOL neutron induced fission method. Calculations indicate that the RIA facility can easily produce at least 150 pnA – which is much more that what is needed to produce ${}^{168}_{70}$Yb almost as cold as possible using the ${}^{82}_{34}$Se(${}^{91}_{36}$Kr,5n) reaction. It is clear that a RIA facility would allow for a new sensitive search for HD in ${}^{168}_{70}$Yb under optimal ultra cold reaction conditions – as well as conditions that are also optimal for detecting the residue in a FMA like mass separator, i.e., using a near symmetric reaction. Thus, with the FMA device, it is possible to gate on reactions that, despite fission, are produced at extreme spins.

nucleus	mass excess [keV]
${}^{136}_{54}$Xe	-86424.445312
${}^{36}_{16}$S	-30663.957031
${}^{124}_{50}$Sn	-88236.101562
${}^{48}_{20}$Ca	-44214.742188
${}^{86}_{36}$Kr	-83265.945312
${}^{87}_{34}$Se	-66582.484375
${}^{82}_{34}$Se	-77593.437500
${}^{91}_{36}$Kr	-71312.921875
${}^{168}_{70}$Yb	-61576.898438
n	8071.323242

Table 2: The mass excess for the isotopes discussed

References

[1] Dudeck at al, PR **B211**(1988)252.

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[4] LaFosse et al., PRL **74**(1996)5186

[5] J.N. Wilson et al., PR **C56**(1997)2502

[6] Galindo-Uribarri et al., PRL **71**(1993)231

[7] Lunardi et al., Proceedings from the Conference on Nuclear Structure at the Limits, ANL, July 22 - 26 1996, page 29.

[8] S. Cohen, F. Plasil and W.J. Swiatecki, Ann. Phys. **82** (1974) 557-596.

[9] http://www.nndc.bnl.gov/nndcscr/masses/MASS_RMD.MAS95